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Properties of Post-AGB Stars

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Abstract. A review is presented of the most relevant results obtained in the last few years on this rare class of astronomical sources. Multi-wavelength analysis of an increasing number of post-AGB stars reveal that they constitute a more inhomogeneous population of stars than previously thought. The new data available allow us to study these sources with unprecedent spatial resolution and to extend our spectroscopic knowledge in a systematic way to the infrared for the first time, where crucial information is contained on the chemical composition of the gas and dust in their circumstellar shells. The overall infrared properties derived from ISO and Spitzer data can be used to trace the mass loss history and the chemical evolution of the ejected material. The new results impose severe observational constraints to the current nucleosynthesis models and suggest that the evolution is mainly determined not only by the initial mass but also by the metallicity of the progenitor star. Post-AGB samples are likely to grow in the near future with the advent of new data from space facilities like Spitzer or Akari. Studies of post-AGB stars in the galactic halo, the Magellanic Clouds and other galaxies of the Local Group will certainly improve our knowledge on the evolutionary connections between AGB stars and PNe.

1. Introduction

Post-Asymptotic Giant Branch (post-AGB, hereafter) stars are low- and intermediate-mass (1–8 $M_\odot$) stars in the transition from the AGB to the planetary nebula (PN, hereafter) stage. This phase of stellar evolution has recently been discussed in detail in excellent reviews by van Winckel (2003) and by Waelkens & Waters (2004), to which the interested reader is referred. In spite of the progress made in the last few years, post-AGB stars, considered as a class, are still far from being completely understood. Two basic reasons exists for this: first, the number of sources which at any given time are evolving along this short-lived ($10^2 - 10^3$ yr) phase in our Galaxy is very small; second, in many cases their evolution takes place completely hidden from our view, as these stars develop thick circumstellar envelopes during the previous thermal pulsing AGB phase, which makes observations in the optical very difficult, if not impossible.

Stars enter the post-AGB at the moment when the strong AGB mass loss stops, which is also accompanied by the end of the stellar pulsations. At this moment, the central star is expected to evolve to higher effective temperatures, reappearing again in the optical range as a consequence of the dilution of the circumstellar envelope on a timescale which is mainly dependent on the initial mass of the progenitor star (Blöcker 1995). Althoug a basic knowledge of the whole process exists, there are still many open issues which deserve further investigation. The mechanism(s) of PN shaping, the dual-dust chemistry phenomenon observed not only in transition sources but also later during the PN stage, or the recent identification of some solid state features which are only detected in post-AGB stars whose carriers are still unknown, are just a few examples of areas where there is still progress to be made, some of which will be here addressed.

2. Recent post-AGB surveys

2.1. *New identifications, atlases and catalogues*

In the last decade a considerable effort has been made in the identification of the missing population of post-AGB stars which may have escaped detection in the old searches carried out in the early 90's. Most of these surveys, although based upon the characteristic excess displayed by these transition sources at IRAS wavelengths, were strongly biased toward candidates showing bright optical counterparts, usually stars located at relatively high galactic latitudes and, as such, belonging to a low-mass population (e.g. Hrivnak et al. 1989; Oudmaijer et al. 1992; Hu et al. 1993; Oudmaijer 1996).

This is not the case of the GLMP catalogue (García-Lario 1992), a colour selected, flux limited sample of IRAS sources which contains more than 250 candidate post-AGB stars, the largest compilation so far available. Actually, only half of these sources show optically bright counterparts, for which low resolution spectroscopy, finding charts and improved astrometric coordinates have recently been compiled in an atlas by Suárez et al. (2006). The rest are heavily obscured stars only detectable in the infrared.

The spectral type distribution shown by the newly classified sources do not show the strong peak at intermediate F-G classes typically observed in *classical* post-AGB samples. In contrast, they display a much flatter distribution of spectral types. Remarkably, the subsample of extremely obscured sources showing no optical counterpart follows a galactic distribution which corresponds to a more massive population (see Figure 1).

More recently, Bayo et al. (in prep.) have used the improved sensitivity and spatial resolution of the MSX galactic plane survey, combined with some of the more recent tools developed for the Astrophysical Virtual Observatory project (`http://www.euro-vo.org`) to carefully cross-match the MSX and IRAS Point Source Catalogues. This way some 100 additional sources have been identified as new, low-galactic latitude post-AGB stars, for which nothing is yet known.

In parallel, Szczerba et al. are building a catalogue where all the information available in the literature on stellar parameters and chemical abundances of post-AGB stars will be collected. Special attention is also given to the infrared spectral features detected by ISO and to the morphology inferred from HST images (Siódmiak et al., these proceedings).

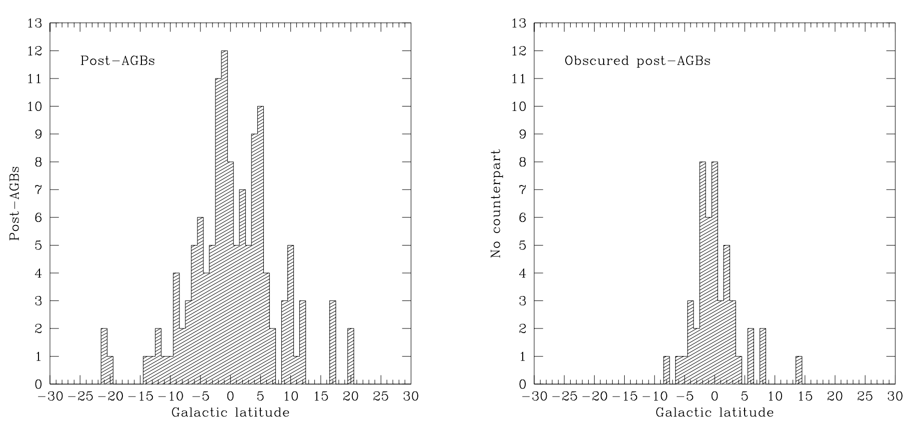

Figure 1. Galactic latitude distribution of *classical*, optically bright post-AGB stars (left) and of the new population of obscured post-AGB stars (right). Note the narrower distribution shown by the obscured sample, which suggests a higher mass population (from Suárez et al. 2006).

2.2. *Morphological surveys*

Studying the early shaping of PNe through morphological surveys with subarcsec resolution is another area where important progress has been made in the last few years, although no conclusion has yet been reached on the physical mechanism(s) which lead to the generation of the macro- and micro-structures later observed during the PN phase (Corradi, these proceedings). Interaction with a binary companion (Livio & Soker 1988) and magnetic fields (García-Segura et al. 1999) continue to be the most popular options.

Following the pioneering survey made with HST/WFPC2 by Ueta et al. (2000), other HST snapshot surveys have been carried out using ACS and NICMOS (see e.g. Sahai et al., these proceedings), extending the observational database in size and wavelength coverage. The results obtained confirm that almost all post-AGB stars are aspherical, sometimes showing complex multipolar morphologies in reflected light.

Additional observations are now being collected from the ground, taking adavantage of the new instrumentation and innovative observing techniques made available at 8 m class telescopes, which are able to compete with the spatial resolution obtained from space with HST, especially at near- and mid-infrared wavelengths, where the detailed morphologies of the dusty waists are better probed. Nice examples were shown at this conference, like the Keck images of a sample of proto-PNe obtained using laser guide star adaptive optics at near infrared wavelengths (Sánchez Contreras et al.); or the VLT interferometric measurements of the peculiar AGB star OH 231.8+4.2 made with MIDI at mid-infrared wavelengths and with the adaptive optics system NACO in the near-infrared (Matsuura et al.). Subarcsec resolution has also been achieved at mid-infrared wavelengths from the ground using OSCIR at the infrared-optimized Gemini telescopes (Kwok et al. 2002; Clube & Gledhill 2004, these proceedings).

2.3. *Molecular hydrogen surveys*

Data collected in the last few years include subarcsecond resolution images of individual sources using integral field spectroscopy (Lowe & Gledhill, these proceedings) as well as low- and high-resolution near-infrared spectroscopy of different samples of post-AGB stars (García-Hernández et al. 2002; Kelly & Hrivnak 2005; Hrivnak, these proceedings). The observations suggest that the fluorescence-excited molecular hydrogen emission is the result of the central star becoming hot enough to produce the necessary UV photons while, in contrast, shock-excited emission is detected at any moment during the post-AGB phase, irrespective of the effective temperature of the central star, in association with bipolar outflows, as a consequence of the interaction of the new, fast post-AGB wind with the older, slow AGB wind.

3. Multi-wavelength analysis of individual sources

3.1. *Properties of classical, optically bright post-AGB stars*

Classical post-AGB stars are usually considered to be slowly evolving, low-mass stars belonging to the old disk population. This is mainly because they show low metallicities (typically from [Fe/H] = −1 to [Fe/H] = −0.3), and a high galactic latitude distribution. The overall SED shows a characteristic double-peak component (see Figure 2), the optical peak corresponding to the bright central star while in the infrared we can see the emission from the cold dust grains in the circumstellar envelope. In the optical, they are affected by little to moderate reddening and when observed with HST they usually show only slightly aspherical morphologies which are detected in scattered light, although in a few cases more complex multipolar morphologies are also observed.

They can be divided in two main subgroups: C-rich sources, which show strong s-process enrichment indicative of an efficient 3rd dredge-up usually accompanied by a 21 μm emission; and O-rich sources, which are not s-process enriched. The latter group may be the result of the evolution of AGB stars with very low progenitor masses which do not experience an efficient 3rd dredge-up (van Winckel 2003).

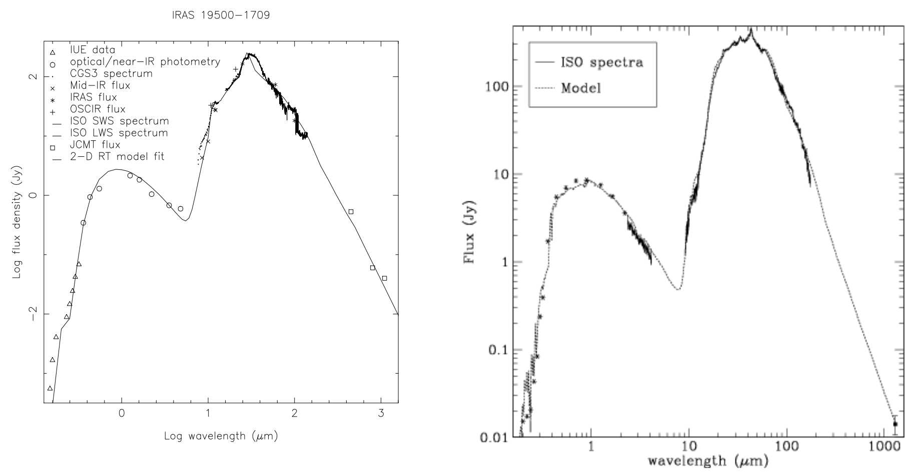

Figure 2. Spectral energy distribution of *classical* post-AGB stars: the C-rich IRAS 19500−1709 (Clube & Gledhill 2004; left); and the O-rich HD 161796 (from Hoogzaad et al. 2002; right).

3.2. *Properties of rapidly evolving, heavily obscured post-AGB stars*

A second class of post-AGB stars is formed by a population of strongly reddened sources characterized by the conspicuous presence of a hot dust component in their SEDs attributed to recent or on-going mass loss (see Figure 3). They are distinguished by a narrower galactic distribution, indicative of higher mass progenitors. Their central stars are usually of B-type suggesting a fast post-AGB evolution. They are surrounded by molecular shells which are in many cases easily detectable in CO or OH at (sub-)milimeter and radio wavelengths. In many cases, shocked-excited molecular hydrogen emission is also detected in association with high velocity outflows and/or a strong bipolar morphology. A few sources belonging to this group show low excitation nebular emission lines, suggesting that the photoionization of the circumstellar envelope has already started.

In extreme cases, these post-AGB stars do not show any optical counterpart at all; sometimes they are neither detectable at near-infrared wavelengths (see e.g. Jiménez Esteban et al. 2006). They must represent a population of high-mass stars so rapidly evolving to the PN stage that never become observable as PNe in the optical. Most of these sources are O-rich, as expected for stars developing hot bottom burning (HBB, hereafter) during the previous AGB phase (Lattanzio 2003), and show strong OH masers. In the infrared they are characterized by the presence of strong amorphous silicate absorption features which are in many cases accompanied by narrow crystalline silicate emission, which is usually interpreted as a consequence of a recent phase of strong mass loss (high-temperature annealing; Waters et al. 1996; Sylvester et al. 1999); or, alternatively, as the result of the presence in the system of a long-lived circumbinary disk (low-temperature crystallization; Molster et al. 1999). A subgroup of them, the so-called *OHPNe*, show also radio continuum emission (García-Hernández et al. these proceedings) and may constitute a new class of *infrared PNe*.

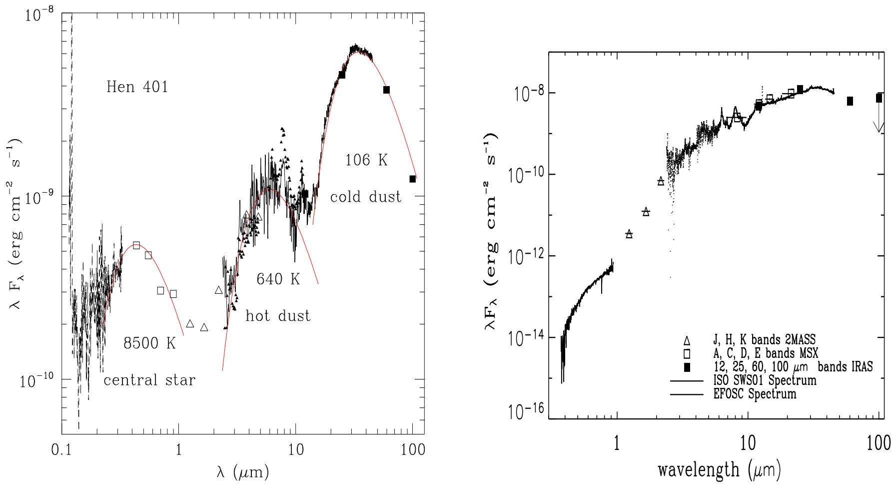

Figure 3. Spectral energy distribution of rapidly evolving, high mass post-AGB stars. The strongly bipolar source Hen 3−401 (from Parthasarathy et al. 2001; left); and the heavily obscured, OHPN IRAS 17347−3139 (from Perea Calderón et al. in prep.; right).

4. The ISO legacy

Our understanding of the post-AGB transition phase has enormously benefited from the results provided by ISO. Based on the analysis of ∼350 ISO spectra of sources spanning the whole evolution from the AGB to the PN stage (65 of them post-AGB stars), an evolutionary scheme has been proposed by García-Lario & Perea Calderón (2003). The scheme takes into account not only the shape of the infrared spectrum but also the evolution of the gas-phase molecular bands and of the solid state features detected in the SWS spectral range. Two main chemical evolutionary branches are identified (see Figure 4) which reflect the continuous increase of optical thickness in the circumstellar shell of AGB stars, as they evolve towards the PN stage, as well as the cool down of the envelope as a consequence of the shell expansion after the end of the strong mass loss phase. Through these sequences we can also follow in detail the process of condensation and growth of the dust grains formed in the stellar envelope until the star becomes a PN. In addition, there is a clear evolution of carbonaceous material from aliphatic to aromatic structures and of the silicates from amorphous to crystalline, as a consequence of the thermal processing of the grains in the envelope.

The ISO spectra of C-rich post-AGB stars show many dust features including the well known emission bands at 3.3, 6.2, 7.7, 8.6 and 11.3 μm generally attributed to PAHs. These features show different shapes and relative intensities as a function of the excitation conditions and grain size (Verstraete et al. 2001; Peeters et al. 2002). Additional bands can be observed at 11–15 μm if the PAHs are highly hydrogenated (Hony et al. 2001); or at 15–21 μm, if they are very large in size (van Kerckhoven et al. 2000). The 21 μm feature, only observed so far in C-rich post-AGB stars and in very young PNe has been attributed to various molecular and solid-state species, and the debate is still open. Among the proposed carriers we find TiC nanocrystals (von Helden et al. 2000); TiC interacting with fullerenes (Kimura et al. 2005); SiC grains (Speck & Hofmeister 2004); or doped SiC grains (Jiang et al. 2005). Also frequently observed in C-rich post-AGB stars is the broad and prominent *30 μm* feature, tentatively identified as MgS (Hony et

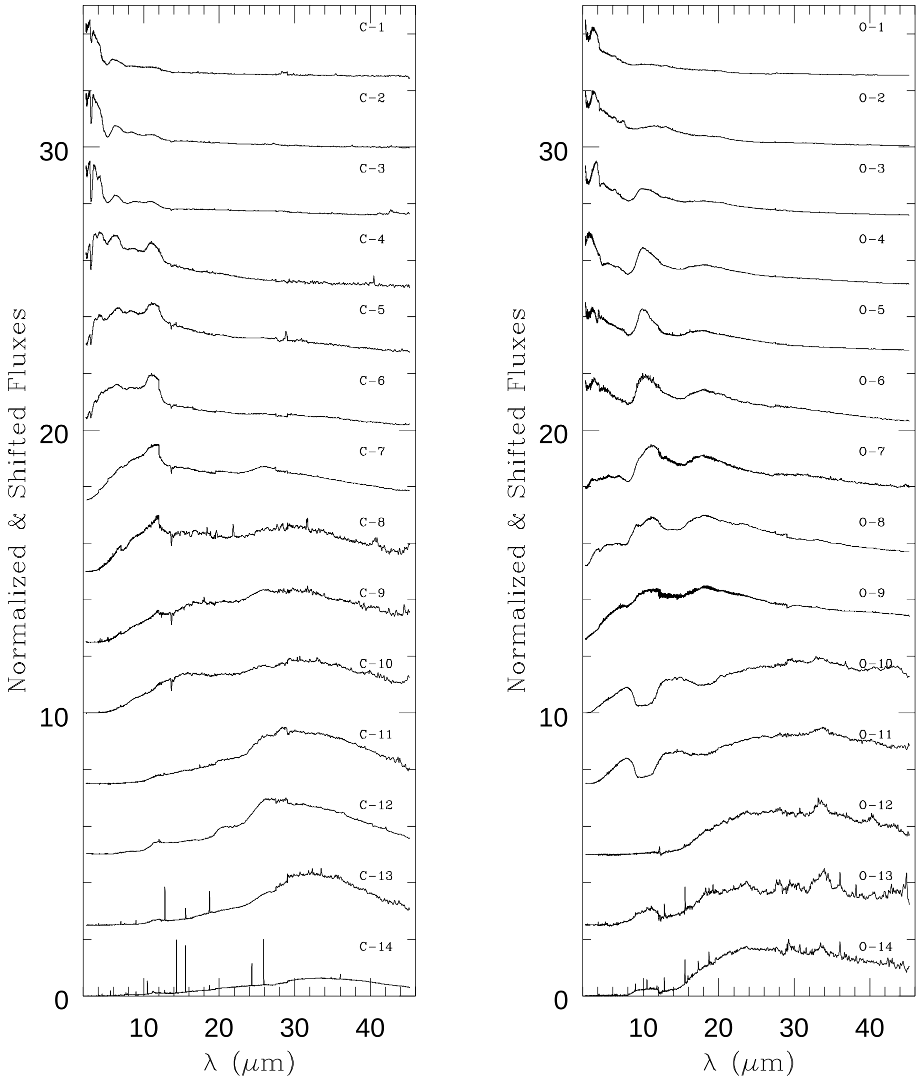

Figure 4. Spectral sequence followed by intermediate-mass C-rich AGB stars (left) and by high-mass O-rich AGB stars (right) in their way to become PNe (from García-Lario & Perea Calderón 2003). A third sequence (not shown) would correspond to the low-mass O-rich stars which do not experience the 3rd dredge-up in the AGB, some of which may never become PNe.

al. 2002), which is actually a mixture of two different features centred at 26 and 33 μm showing a variable shape and strength from source to source (Volk et al. 2002).

In the case of the O-rich AGB stars, the spectral evolution is characterized by the increasing strength of the amorphous silicate emission bands at 9.7 and 18 μm, which can eventually turn into absorption when the mass loss rate reaches its maximum value at the end of the thermal pulsing AGB phase. At this moment, prominent crystalline silicate features take over at 19.8, 23.5, 27.5, 33.5, 40.8, 43.3 and 60 μm which remain visible during the whole post-AGB evolution. They are mostly Mg-rich olivine and pyroxenes (Molster et al. 2002) but other forms like diopside, enstatite, forsterite (with different relative contents of Mg and Fe) are also detected. Water ice at 3.1 μm and at 43 and 62 μm is additionally observed only in the most heavily obscured and extremely bipolar sources (e.g. IRAS 16342−3814, Sahai et al. 1999; IRAS 22036+5306, Sahai et al. 2003; or IRAS 17423−1755, García-Lario et al. in prep.). The freezeout of water onto dust grains requires low temperatures and high densities which are characteristic of the shielded outer regions of the dusty torii seen in the HST images of these stars.

5. Post-AGB chemistry and stellar evolution

Nucleosynthesis models predict the evolution of AGB stars along different chemical paths as a function of the initial mass of the progenitor star. If correct, they should also be able to explain the chemical segregation observed in post-AGB stars and in PNe.

Although all stars are born O-rich, reflecting the chemical composition of the ISM, nuclear burning products brought to the stellar surface during the thermal pulsing AGB phase (in the so-called *3rd dredge-up*) can eventually turn the star into C-rich (and s-process enriched) before it enters the post-AGB phase. This 3rd dredge-up is actually expected to achieve its maximum efficiency in stars with masses in the 1.2 to 3.0 $M_\odot$ range, which will become C-rich after a few thermal pulses ending their AGB lifetime as C-rich post-AGB stars. These stars will follow the evolutionary sequence shown in the left panel of Figure 4. In contrast, low-mass stars ($M<1.2\ M_\odot$) may not experience any significant dredge-up during the AGB phase (Gallino et al. 2004) and will stay O-rich during the whole AGB-PN evolution. This population of low-mass stars can be identified with the *classical* O-rich post-AGB stars not s-process enriched already described in this paper. Above 3-4 $M_\odot$, the activation of the HBB will also prevent the transformation of O-rich AGB stars into C-rich sources. The infrared evolution of these high-mass stars is probably well represented by the spectral sequence shown in the right panel of Figure 4. Recent observations of heavily obscured O-rich AGB stars confirm that they are actually HBB stars (García-Hernández et al. these proceedings) and they are suspected to be the progenitors of N-rich type I PNe. Low-mass O-rich AGB stars would follow a similar spectral evolution but in this case the silicate bands may never turn into absorption, as these stars are not expected to develop thick circumstellar shells.

Metallicity effects cannot be ignored, and actually they seem to play an important role in the definition of the mass limits which determine the chemical dicotomy observed. In particular, the efficiency of dust production is expected to decrease at low metallicities, as well as the mimimum mass needed for the activation of the HBB or the number of thermal pulses needed to invert the C/O ratio (this would explain the higher proportion of C-rich PNe detected in the Magellanic Clouds). Implications on AGB lifetimes and on initial/final mass ratios should carefully be considered in future studies.

6. The future

Additional post-AGB samples are expected to become available soon with the advent of new data from Spitzer and Akari. If we can extend the analysis to sources located in the Galactic Bulge, the Galactic halo, the Magellanic Clouds and other galaxies of the Local Group we will be able for the first time to probe the effect of different metallicity environments on the observed evolution. Some results were already presented at this conference based on Spitzer data (like e.g. the detection of the first extragalactic post-AGB star in the LMC by Bernard-Salas et al.; or the analysis of a few heavily obscured OHPNe in the direction of the Galactic Bulge by García-Hernández et al.), and we expect to see many more new exciting results in the very near future. Determining the stellar yields returned by low- and intermediate-mass stars to the ISM as a function of the metallicity will certainly improve our knowledge on the chemical evolution of galaxies.

High spatial resolution observations in the mid-infrared with narrow filters will help to determine the relative distribution of O-rich and C-rich dust in transition sources showing a dual chemistry and study the connection with [WC]-type PNe, where the same phenomenon is observed (Perea-Calderón et al., these proceedings). Finally, thanks to the improved sensitivity and spatial resolution to be provided soon by the Herschel Space Observatory we will be able to search for extended far-infrared emission around post-AGB stars. Determining the radial density distribution of the dust will be essential to recover the mass loss history experienced by low- and intermediate-mass stars in the previous AGB phase, a fundamental ingredient in all evolutionary models.

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